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DENDROCHRONOLOGY OF UTAH JUNIPER (*JUNIPERUS OSTEOSPERMA* (TORR.) LITTLE)

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ABSTRACT

Utah juniper was a foundational species for the discipline of dendrochronology, having been used in the early 20th Century investigations of Mesa Verde, but has been largely ignored by dendrochronologists since. Here we present dendrochronological investigations of Utah juniper core and cross-sectional samples from four sites in northern Utah. We demonstrate that, contrary to the general opinion among many dendrochronologists, Utah juniper exhibits excellent crossdating that is reflective of its sensitivity to climate — a desirable characteristic for dendroclimate reconstruction. Across all four sites the dominant signal for annual ring-width increment occurred during the growing season and was positive for precipitation and negative for temperature. This corroborates ecophysiological studies that highlight Utah juniper's aggressive water-use behavior and desiccation tolerance that together enable survival at extremely negative soil water potentials. This behavior differs from co-occurring *Pinus* spp. (*i.e. P. edulis* and *P. monophylla*) that avoid cavitation at the cost of carbon starvation. We determine that the annual radial increment of Utah juniper rings is particularly responsive to soil moisture availability, and is in fact a useful proxy for hydroclimatic variables such as precipitation, drought, and streamflow. Its geographic distribution spans a large swath of the Interior West, including areas where other more commonly sought-after species for dendrochronology do not occur, and ought to be considered crucial for complementing the rich network of tree-ring chronologies in the western U.S.

Keywords: anisohydric, dendrochronology, dendroclimatology, drought-sensitive, pinyon-juniper, Rocky Mountain juniper, Utah.

INTRODUCTION

Utah juniper (*Juniperus osteosperma* (Torr.) Little) played a foundational role in the dating of Mesa Verde (Douglass 1929), a study that was pivotal for establishing dendrochronology as a respected discipline (Fritts *et al.* 1965). In the first issue of the *Tree-Ring Bulletin*, while making a comparison to Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) beams, McGregor (1934) noted "The one specimen of juniper [species unknown] … is most outstanding in the excellence of its record, a fact which is unusual in the experience of reading tree rings." In addition to early use in dendroarchaeology, Dean and Robinson (1978) indicated that *Juniperus* spp. tree-ring series were included in many of the chronologies associated with the Southwestern Paleoclimate Project as early as the 1960s. This project likely included Utah juniper series, although the *Juniperus* were not specified to species. In the days since, however, Utah juniper has become an overlooked and underutilized species that is widely considered unusable

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for dendroclimatic research. Utah juniper is widespread from California to the Colorado Rockies, and from southern Montana to northern Mexico (Figure 1), occurring at lower elevations oftentimes on the ecotone between rangeland and woodlands. Utah juniper is associated with both pinyon species – common pinyon (*Pinus edulis* Engelm.) and singleleaf pinyon (*Pinus monophylla* Torr. & Frem.) that are highly sought-after for dendrochronological studies. However, because Utah juniper is found at lower, drier elevations than either pinyon species (Figure 2) it is likely to be even more precipitation and temperature sensitive than pinyon and especially higher elevation species (Fritts 1976; Hidalgo *et al.* 2001). Given that Utah juniper is likely to capture low elevation hydroclimate widely across the West, and considering the dendrochronological principle of site selection, it is surprising that this long-lived species has not been exploited for dendroclimatology (*e.g.* no Utah juniper chronologies are in the International Tree-Ring Data Bank as of August 2015).

The primary reason that Utah juniper, and to a lesser extent its close relative oneseed juniper (*Juniperus monosperma* (Engelm.) Sarg.), have been avoided in dendrochronology is their reputation for being difficult, if not "impossible," to crossdate (Towner *et al.* 2001). The origin of this sentiment is unclear, although it is obvious from early archaeological literature that crossdating Utah juniper was challenging but possible. Nash (1999, p. 209) notes that "*conclusive crossdating in juniper had not yet been demonstrated in 1938*," citing a letter that documents archaeologists carefully choosing large specimens of juniper while discarding smaller pieces of pinyon, a practice that dendrochronologists found imprudent: "*It was fortunate that a Dendrochronologist was on the expedition, as the wood (charcoal) was at least 90% juniper, all nice specimens, which could be ignored, [but] it was from the scattered bits of pinyon that dating was possible….*". Nevertheless, it is clear that Utah juniper was crossdated and used extensively in the Wetherill Mesa Project in the late 1950s and early 1960s (Fritts *et al.* 1965). More recent dendroarchaeological literature has suggested the construction of Utah juniper chronologies might improve project-related crossdating success (Towner *et al.* 2009).

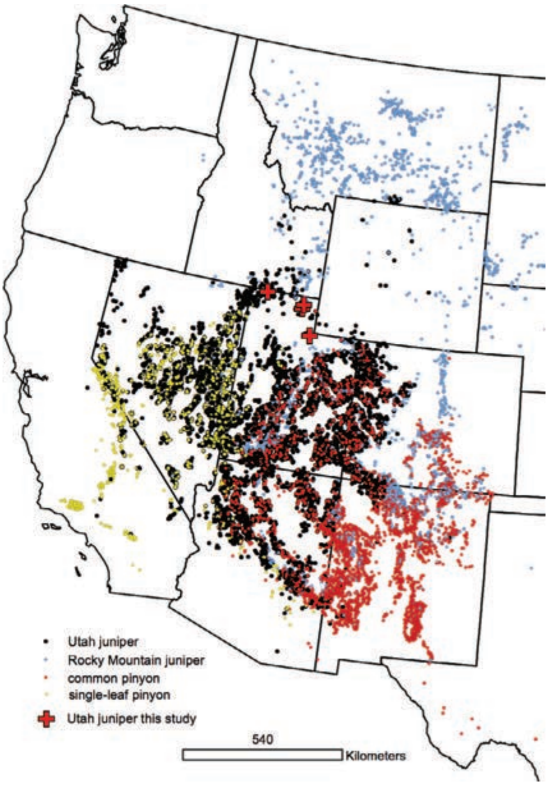

Figure 1. Geographic distribution of four co-occurring species (Utah juniper, Rocky Mountain juniper, common pinyon, and singleleaf pinyon), and the four sites from this study. Locations are from a full measurement (2003–2012) of the Forest Inventory and Analysis Database (http://apps.fs.fed.us/fia/fido/index.html) and include any tree taller than 15 cm.

One challenge to crossdating Utah juniper is its propensity for absent rings (Figure 3a). Similar to other species in semiarid areas of the western United States (St. George *et al.* 2013), it is likely there is a range of the percentage of absent rings one would encounter in a chronology from a particular site. However, locally absent rings are more a function of how trees native to arid/semi-arid climates survive extreme drought rather than a trait inherent to Utah juniper. Trees survive prolonged environmental stress (*i.e.* carbon limitation) by allocating carbon to that part of the tree that gets the greatest resource return on carbon investment (Mäkelä 2012). This allocation pattern describes enhanced leaf area, shoot elongation, reduced

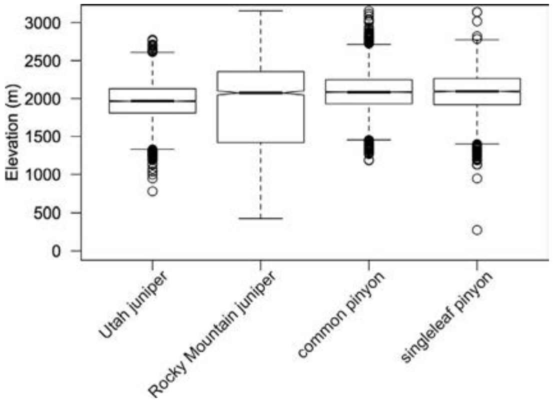

Figure 2. Boxplot of elevation ranges for species-specific locations in Figure 1 from Forest Inventory and Analysis Database (http://apps.fs.fed.us/fia/fido/index.html). Boxes span the 1st to 3rd quartiles, whiskers denote 1.5 times the interquartile range, the heavy horizontal line inside the boxes indicates the median, and open circles indicate outliers. Notches that do not overlap indicate probable significant differences between medians (Chambers *et al.* 1983).

root growth in light-limited understories (Ogle and Pacala 2009), crown dieback, and reduced transpiring leaf area, all in response to drought (Dobbertin 2005). In particular, given the stress of increased water demand, conifer species that are native to arid/semi-arid regions sacrifice the production of cambial plumbing and leaf area (Corcuera *et al.* 2012), for greater carbon allocation to fine roots, which can exploit more soil volume and increase water uptake (Kerhoulas and Kane 2012). Sacrificed xylem can result in one to many years with incomplete (locally absent; *i.e.* absent at specific or "local" places around the stem) or entirely missing rings (*i.e.* absent everywhere on the bole of the tree, a hypothetical situation that is unlikely to occur). Locally absent rings are not uncommon for species native to the western U.S. but are much rarer in tree-ring chronologies outside the U.S. West (St. George *et al.* 2013).

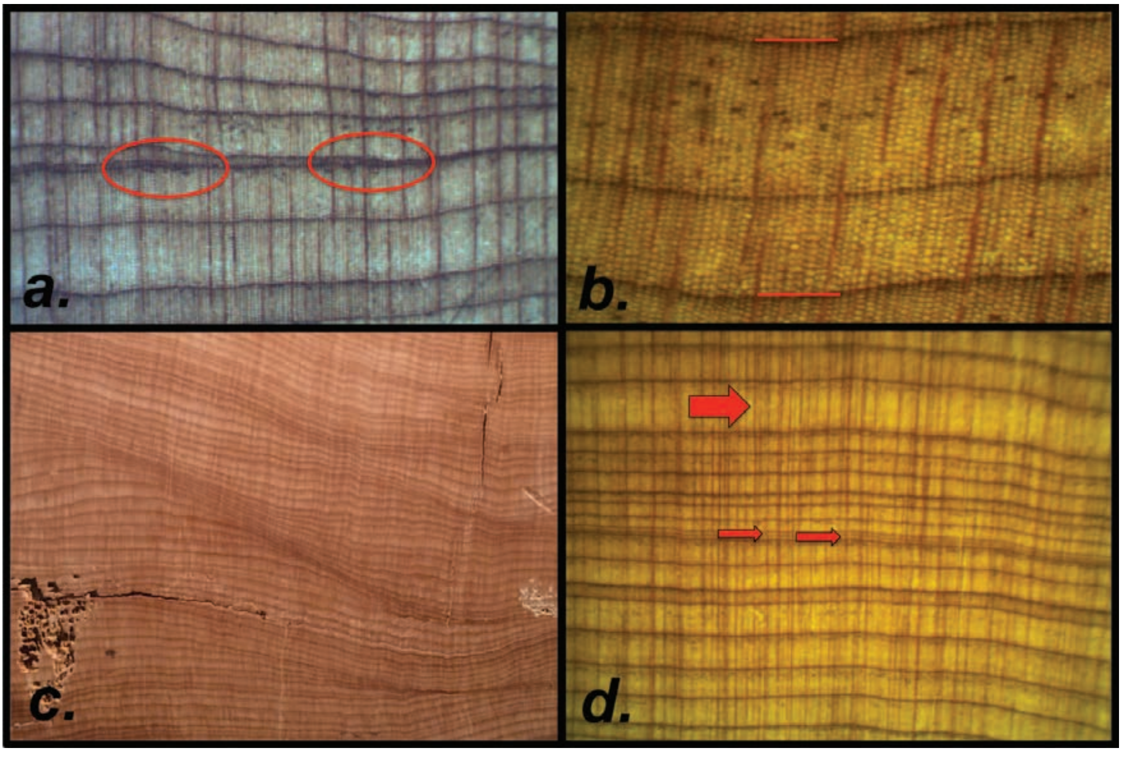

Figure 3. Some common ring-width features in Utah juniper: (a) two consecutive wedging (locally absent) rings, (b) a false ring (red lines delineate one annual ring), (c) an area of extreme tangential nonuniformity in ring width, (d) an example of strong inter-annual sensitivity. Arrows indicate one very wide and two very narrow rings.

Perhaps the most formidable challenge to crossdating Utah juniper involves its propensity to produce "false rings" – intra-annual bands of lignified cells that mimic true latewood bands (Figure 3b). Although not documented, we suspect that false ring formation is the primary reason Utah juniper has been largely ignored, in particular in the extreme Southwest where the North American Monsoon is prevalent. In this region, depletion of cool-season moisture prior to monsoon onset results in a growing season drought that triggers latewood formation (Griffin *et al.* 2013). Subsequent monsoon precipitation shifts wood production back to cells that look like earlywood, resulting in false rings, a process observed in other conifer species (Hoffer and Tardif 2009). Recent work in the Southwest quantified earlywood-latewood boundaries, by identifying false rings, and has resulted in a more accurate characterization of the prehistoric North American Monsoon (Griffin *et al.* 2013). Given demonstrated hydroclimatic control on false-ring formation, and the extraordinarily large geographic extent of the species (Figure 1), we hypothesized that Utah juniper in the eastern Great Basin, where the summer monsoon is largely absent, would lack significant false rings.

A final, pragmatic reason Utah juniper has likely not been widely used for dendroclimatology is the availability of species easier to work within much of the western U.S., namely the pines and Douglas-fir, which putatively exhibit fewer absent and false ring issues and reliably crossdate (Grissino-Mayer 1993). We suspect researchers working in areas with common pinyon, singleleaf pinyon, ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), and also low-elevation Douglas-fir at their disposal would typically eschew junipers as the other species have the reputation of being easier to work with.

In northern Utah, a region where the dendroclimatology workhorse species (*i.e.* singleleaf pinyon, common pinyon, and ponderosa pine) are conspicuous by their absence, it was a necessity to obtain other desirable climate proxies. Although Douglas-fir is common in the region, individuals older than *ca*. 400 years are extremely rare because of historic resource extraction in low elevation stands (Bekker and Heath 2007). Furthermore, Douglas-firs in the region have generally exhibited low variation in year-to-year ring-width increment (*e.g.* chronologies UT536, UT537, and UT538 in the ITRDB). As a result, Utah juniper and Rocky Mountain juniper (*Juniperus scopulorum* Sarg.) were the only regionally available species likely to be sufficiently sensitive to climatic variables. Although there is a precedent for using Rocky Mountain juniper chronologies in dendroclimatology (Allen *et al.* 2013; Spond *et al.* 2014), to our knowledge none exists for Utah juniper apart from the possible inclusion of tree-ring series in the early work of Douglass, Dean and Robinson (1978), and Fritts *et al.* (1965).

Our objective is to demonstrate the dendrochronological value of Utah juniper as a climate proxy for the Intermountain West. Our goals are fourfold: first, we aim to document the crossdating success based on both cross-sections and increment cores. Second, we explore the temperature and precipitation responses of four separate Utah juniper chronologies and speculate on their ecophysiological basis. Third, we explore the possibility for climate reconstructions based on Utah juniper. Fourth, we detail sampling, preparation, measurement, and crossdating lessons to take into consideration before using this species.

METHODS

Regional Climate

The Utah juniper tree-ring chronologies developed for this study were collected at four sites in northern Utah, three of which are considered the western edge of the Rocky Mountains and one squarely situated in the Great Basin (Figure 1). Climate for the region exhibits two principal characteristics. First, a unimodal seasonal distribution of precipitation centered on the October-September water year results in annual precipitation that is dominated by winter snowfall delivered by storms originating in the Pacific Ocean (Mock 1996; Brown and Comrie 2004). Second, North American Monsoon moisture rarely materializes this far north (Mock

1996) resulting in an extended dry season during the summer months.

Tree-Ring Collection

We identified four locations to sample Utah juniper (Figure 1; Table 1). Card Canyon (CCU) and Left Hand Fork (LFU) were located in separate canyons immediately east of Logan, Utah in the Bear River Mountain range. The South Fork Chalk Creek (SFC, Figure 4) site was located approximately 50 km to the south of LFU in the rain shadow of the Wasatch Mountain range east of Salt Lake City, Utah. The Raft River (RRU) site was located in the east-west-trending Raft River Mountains in the Sawtooth National Forest of northwestern Utah. All sites were at low elevations on generally south-facing, steep, rocky slopes and/or ridge tops with poor soil development where we presumed water was the factor most limiting to growth. As per standard protocols for dendroclimatology (Stokes and Smiley 1968), we took at least two cores per tree where possible or obtained cross-sections from the lower boles (Table 2).

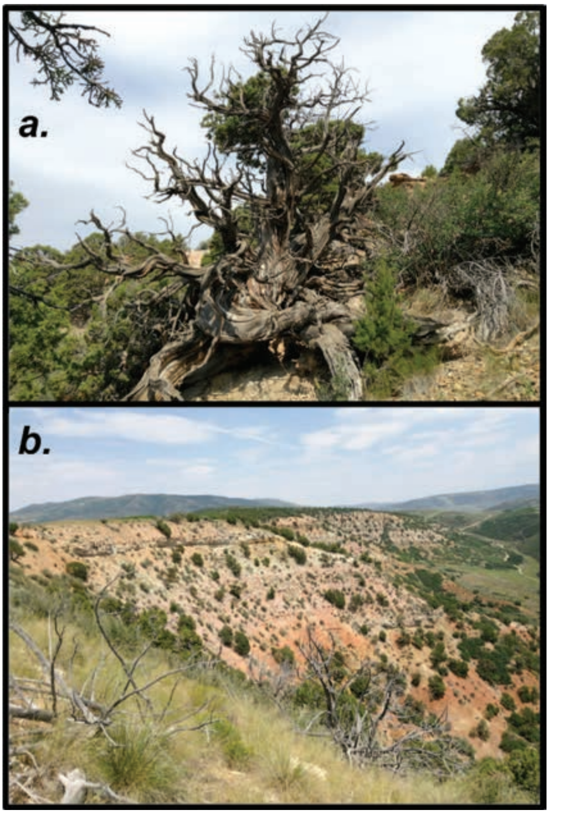

Figure 4. (a) Old individuals of Utah juniper commonly exhibit substantial proportions of dead structure, and (b) typically occur on marginal sites where they do not have to compete with other vegetation as exemplified by the steep, south-facing SFC site with minimal soil development.

Sample Preparation

Samples were prepared with progressively finer sandpaper to *ca*. 600 grit and *ca*. 9 micron finishing film, until individual cells were clearly visible under a binocular microscope. The tree-ring series were then crossdated using skeleton plots, the list, and memorization methods (Speer 2010) to assign a precise calendar year to each ring. The rings were then measured to 0.001 mm, and dating accuracy was checked using the computer program COFECHA (Holmes 1983; Grissino-Mayer 2001). For all sites, we used a 50-year correlation window overlapped by 25 years. Finally, to develop tree-ring indices we used a modified negative exponential curve on series that exhibited classic growth and a mean on the others. We inspected the detrended series individually to ensure that variation that was less common among all series was removed. Series were averaged using a biweight robust mean into a standardized index for each site.

Analyses

To characterize the successful crossdating of Utah juniper we reported the interseries correlation coefficient, mean sensitivity, and percentage of missing rings from the COFECHA output. To assess the inequality in year-to-year ring width, we calculated the Gini coefficient for the common period AD 1664–2010 between the four chronologies (Biondi and Qeadan 2008). Strength of the chronologies was assessed after calculating the expressed population signal (EPS) and the effective signal (rbar) using 50-year overlapping windows (Wigley *et al.* 1984). First-order autocorrelation was calculated to explore the effects of climatic persistence in the standard chronologies. Pearson's

Table 1. Site-level attributes of the four Utah juniper chronologies.

Site	Latitude	Longitude	Elevation (m)	Geological substrate	Mean annual precipitation (cm)	Mean Maximum Monthly Summer Temperature (°C)
Card Canyon (CCU)	41.76	−111.66	1700	Sugary-textured dolostone[1]	53.8	9.8
Left Hand Fork (LHU)	41.65	−111.71	1980	Sandy dolostone[1]	75.2	7.9
Raft River (RRU)	41.96	−113.32	1828	Metamorphosed trondhjemite and pegmatite[2]	39.8	9.0
South Fork Chalk Creek (SFC)	40.92	−111.21	2160	Sandstone conglomerate, siltstone, and claystone[3]	33.7	10.2

[1]Geologic substrate for CCU and LHU from (Dover 1995).
[2]Geologic substrate for RRU from (Compton 1975).
[3]Geologic substrate for SFC from (Bryant 1994).

correlation coefficient among sites was conducted to look for regional similarity in Utah juniper chronologies. To demonstrate further possible linkages with hydroclimate, we explored general patterns between precipitation and attributes of the Utah juniper chronologies in this study.

To explore how Utah juniper responds to climate, we correlated the standard chronology to monthly total precipitation and monthly maximum temperature. Monthly climate data were extracted at the grid cell for each site from the Parameter-elevation Regressions on Independent Slopes Model (http://www.prism.oregonstate.edu/). We then conducted site-specific bootstrapped correlation function analysis to generate confidence intervals with $\alpha = 0.05$. The chronologies were treated as the predictand and the monthly data beginning in January of the previous calendar year through December of the current calendar year as predictors. We chose this extended period because it fully encompasses the water year and growing season, and it also allowed us to explore potential idiosyncrasies of the relatively unknown climate response of Utah juniper. We also tested for temporal consistency in the climate relationships using a moving-window correlation function analysis that considered 25-yr periods overlapped by 5 years from 1895 to 2010. All analyses were conducted in the R statistical environment (R Development Core Team, 2012) using packages bootRes (Biondi and Waikul 2004; Zang and Biondi 2013) and dplR (Bunn 2010).

RESULTS AND DISCUSSION

Demonstrated Crossdating

Interseries correlation coefficients from the four sites indicated moderate to strong crossdating strength (Table 2). Cross-sections aided in initial dating at sites CCU and LFU, but were not ultimately required to crossdate trees at any of the sites. The resultant chronologies ranged in length

Table 2. Site-specific chronology statistics from COFECHA (Holmes 1983).

Site	Interseries correlation	Mean sensitivity	Gini coefficient[a]	First-order autocorrelation	Number of trees (series)	Mean series length	Percent absent rings	Time span (at least two cores)
CCU	0.661	0.269	0.142	0.68	20 (53)[b]	277	0.075%	1338 (1353)–2012
LFU	0.555	0.295	0.153	0.59	10 (27)[c]	187	0.236%	1664 (1664)–2012
RRU	0.860	0.529	0.257	0.26	7 (13)	207	1.076%	1634 (1640)–2010
SFC	0.844	0.464	0.237	0.48	25 (45)	241	0.910%	1426 (1456)–2013

[a]Gini coefficient calculated on the standard chronology for the period 1664–2010.
[b]Forty series from twelve trees are cross-sections.
[c]Seventeen series from five trees are cross-sections.

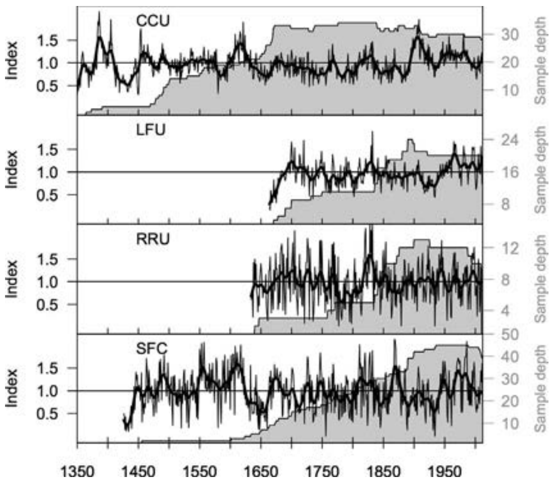

Figure 5. Standard chronologies and their sample depth for the four Utah juniper sites (Table 1). Thick black line is a 20-year cubic smoothing spline with 50% frequency cut-off.

from 348 to 674 years (Table 2, Figure 5). As is commonly the case in dendroclimatic analysis, EPS and rbar were generally greater than their commonly accepted thresholds with sufficient sample depth (Figures 5 and 6). For sites with lower interseries correlations (CCU and LFU), EPS dropped below 0.85 when the number of trees (not series) decreased from 11 to 7, and to <5, respectively. However, in RRU and CCU, EPS did not drop below 0.85 until the number of trees decreased to 2. Only at sites RRU and SFC did rbar exceed a 0.5 threshold (Figure 6). The chronologies exhibited moderate to high sensitivity among sites, corroborated by the Gini coefficient (Table 2). The Gini coefficient for two sites (RRU and SFC) was among the highest reported for common pinyon by Biondi and Qeadan (2008).

Although the sites were located fairly close to each other regionally, the correlation among site chronologies was statistically significant, but variable ($p < 0.001$, Table 3). This was most exemplified by CCU and LFU, which are *ca.* 5 km apart. Similarly, the correlation between the Utah juniper chronologies and the closest existing chronologies in the ITRDB, Rocky Mountain juniper (JTR, ITRDB UT532, Allen *et al.* 2013) and common pinyon (TNR, ITRDB UT533, Bekker *et al.* 2014), was also significant, but not strong (Table 3). This suggested that while Utah juniper exhibited at least some spatiotemporal autocorrelation that is expected among chronologies within a region, it also has a large amount of site-specific information. First-order autocorrelation varied widely between the sites (0.26–0.68, Table 2). Finally, Utah juniper is listed in the Dendrochronology Species Database (http://www.wsl.ch/dienstleistungen/produkte/glossare/dendro_species/about_EN), and Grissino-Mayer (1993) as having a Crossdating Index (CDI) of "1", meaning that it is "a species known to crossdate within and between trees" but not across a region, and is thus of "minor importance to dendrochronology." Based on our crossdating results, we suggest Utah juniper be elevated to a CDI of 2.

Climate Response

There was striking similarity among sites in the response of the chronologies to monthly climate variables. All four sites were strongly positively correlated to growing season precipitation (March–June), and all of the sites except CCU also had a positive relationship to cool-season precipitation (Figure 7). Persistence in the response was indicated by the significant correlation with previous March at CCU, and with previous June at the other sites. The response to precipitation was consistent from April through June at CCU and LFU, from March through July at RRU, and from March through June at SFC. Cool-season precipitation response was consistent from November through January at LFR, October and December at RRU, and from October through December at SFC (data not shown).

Similar to precipitation, all four chronologies showed clear responses to monthly maximum temperature. All sites exhibited a strong negative relationship to temperature from April or May through July or August, except LFU, which was only significant during June (Figure 7). Also like precipitation, each site exhibited a significant response to previous growing-season temperature in June and/or July. CCU exhibited a significant negative response from April through August, and LFU exhibited an unexpected positive response to cool-season temperature from January through

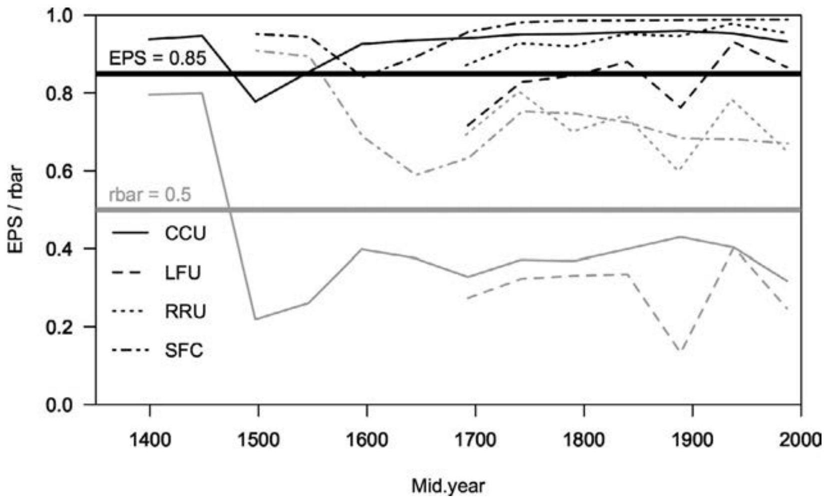

Figure 6. Expressed population signal (EPS) and effective signal (rbar) for the four Utah juniper chronologies (Table 1) calculated using a moving window of 50 years. An EPS threshold of 0.85 is depicted in black, and an rbar threshold of 0.5 is depicted in gray.

March (Figure 7). The negative response to temperature was consistent from May through August at CCU, and June and July at LFU. At RRU a consistent response was found for March through July and for cool-season October through December. At SFC a consistent response occurred April through July, and for previous October and November (data not shown).

Although our Utah juniper sites occur in areas of differing climate and substrates (Table 1), their response to monthly climate was strikingly similar. We suspect that the degree to which series at a given site intercorrelated was driven primarily by the amount of moisture available during the growing season (Figure 8). The observation that previous-year maximum temperatures were negatively related to ring-width increment of the current growing season (at least for SFC) corroborate the findings of Spond *et al.* (2014) for Rocky Mountain juniper. One possible explanation is that cavitated tracheids do not refill during the winter, thereby increasing hydraulic resistance. This ultimately reduces flow to the crown until a milder subsequent growing season results in the growth of additional xylem and phloem. In fact, some unique insights can be drawn from the limited ecophysiological literature that both explain the Utah juniper climate response, and hint at its potential use in dendroclimatology.

Ecophysiology

Plants broadly exhibit two distinct behaviors for managing atmospheric and soil water deficit: anisohydric behavior maintains relatively constant gas exchange at the cost of variable xylem water potential and increased cavitation risk, whereas isohydric behavior maintains relatively constant xylem water potential at the cost of reduced gas exchange and carbon gain, with less risk of cavitation (Tardieu and Simonneau 1998). Utah juniper is an example of an anisohydric species (West *et al.* 2007) that adapts to seasonal low-elevation drought by maximizing early-season surface soil water depletion (Leffler *et al.* 2002) then progressively increases water uptake from deep roots that maintain some degree of gas exchange (Peek *et al.*

Table 3. Pearson's correlation coefficients between chronologies for the period AD 1664–2010. All values significant at $p < 0.01$.

	CCU	LFU	RRU	SFC
LFU	0.622			
RRU	0.470	0.483		
SFC	0.454	0.396	0.510	
LFR[a]	0.654	0.708	0.516	0.552
TNR[b]	0.345	0.425	0.502	0.622

[a]LFR is UT531 in the ITRDB.
[b]TNR is UT533 in the ITRDB.

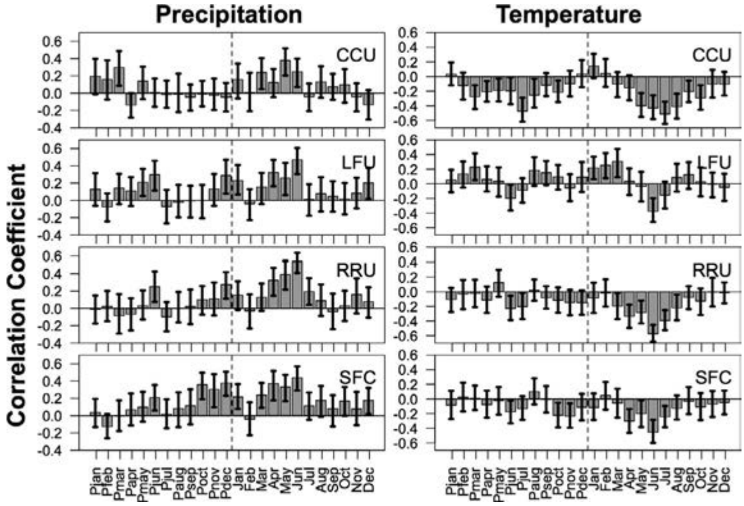

Figure 7. Bootstrapped correlation function analysis for monthly precipitation and maximum monthly temperature from previous-year January (Pjan) through current-year December (Dec).

2006). Concurrently, xylem water potential adjusts to more negative values (down to nearly −7 mPa) to deplete water further through hydraulic lift to keep the surface roots alive and gain some level of gas exchange (Leffler *et al.* 2002; West *et al.* 2007).

Utah juniper's anisohydric behavior and relatively low elevation habitat are attributes that add value to dendroclimatological reconstructions. Utah juniper may be able to more effectively capture the variability in extreme wet and dry years. By depleting more water deeper in the soil to sustain some gas exchange, ring increment is likely to be proportional to extreme dry years. Reciprocally, in extreme wet years a deeper root zone would likely hold more water to sustain growth longer into the growing season. Moreover, an extreme wet year at Utah juniper's low elevation habitat would mean more of the growing season with slow soil water depletion and greater gas exchange. High sensitivity to extremes might explain why Utah juniper's ring-width increment variability (*i.e.* Gini coefficient or average sensitivity) was among the highest of western U.S. species for two of our sites. By contrast, ring increment of isohydric species may reach a floor, or the tree dies, at less severe soil and atmospheric water deficits (Williams *et al.* 2013).

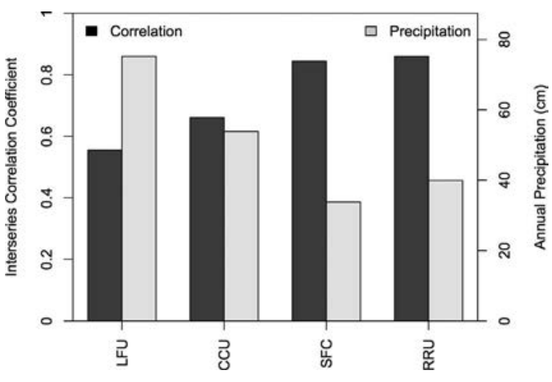

Figure 8. Interseries correlation coefficient from COFECHA and total annual precipitation (cm) for each of the four Utah juniper sites suggest that as water-year precipitation decreases the interrelationship in ring-width increment increases (r = 0.96, p < 0.01).

Dendroclimatic Possibilities

The strong responses to both precipitation and temperature found for Utah juniper ring width, in combination with its anisohydric strategy, suggest it is a good proxy for soil moisture availability (*i.e.* drought or the Palmer Drought Severity Index). Additionally, correlation function analysis of cumulative monthly precipitation and average multi-month temperature averages (*sensu* Meko *et al.* 2011) showed precipitation was the primary determinant of ring width. Indeed, we have found Utah juniper is a very strong proxy

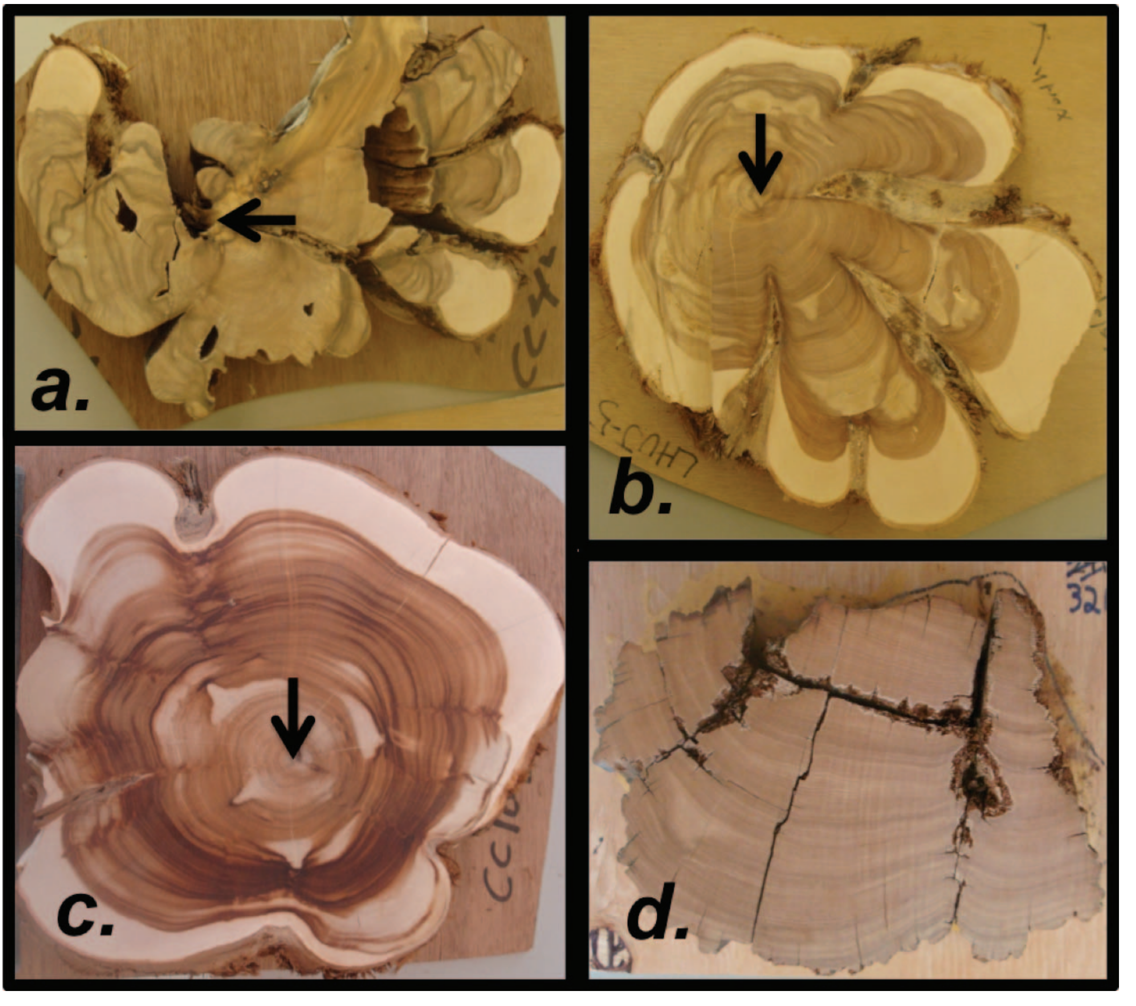

Figure 9. Cross-sections of Utah juniper collected from northern Utah. (a) Extreme lobing and extensive partitioning of mortality, (b) extreme lobing but complete sapwood, (c) reasonable circuit uniformity and dark brown coloration indicative of Utah juniper, (d) sub-fossil wood from SFC, no pith present, sapwood is entirely deteriorated. This specimen dates to the 11th and 12th Centuries. Arrows indicate pith where present.

for regional streamflow (DeRose *et al.* 2015). Given the strong direct relationship between ring width and soil moisture conditions, we suspect dendroclimatic reconstructions with Utah juniper may better capture extreme wet events than isohydric species. Utah juniper is also capable of substantial longevity (up to *ca*. 700 years in this study, and ring counts over 1000 years by the authors), which is desirable for dendroclimatic reconstructions. Furthermore, in combination with remnant wood, which is common on these dry sites (Figure 4), dendrochronologists can extend Utah juniper chronologies back over 1200 years (DeRose *et al.* 2015).

Lessons Learned

Missing rings were certainly a part of all our Utah juniper chronologies (Table 2; Figure 4a). For example, at SFC, 1934 was missing in 75% of samples and 1756 was missing in 83%. However, with a sufficient quantity of increment cores (>20 trees), or a few cross-sections from younger trees, we were able to resolve locally absent ring issues. We suspect part of the reason we saw little evidence for many missing rings was that northern Utah is characterized by generally greater cool-season precipitation than the lower latitudes of Utah juniper distribution (*i.e.* the Southwest, Moore *et al.* 1999). In particular, because it is likely that Utah junipers at northern latitudes do not have shallow fine roots to take advantage of limited summer moisture (West *et al.* 2007; and see North American Monsoon Discussion below), we speculate that at lower latitudes, where cool-season precipitation is proportionally smaller than growing-season precipitation, Utah juniper would have a higher percentage of missing rings.

Word-of-mouth reports from fellow dendrochronologists led us to believe that false rings would be an even greater problem. However, we found relatively few convincing false rings in our samples, whether in cores or cross-sections (Figure 3b). We attribute this to the strong unimodal precipitation distribution for the region, and the lack of any significant amounts of late growing-season precipitation (North American Monsoon-derived, or otherwise). Utah juniper ring-width increment in the region we studied was driven by precipitation originating from the previous winter into the spring and summer of the growing season. Presumably temperatures help control how long the precipitation is available to the trees. Regardless, a second pulse of precipitation during the growing season is virtually absent at these latitudes. The result is generally the normal formation of earlywood to latewood in the Utah juniper we studied (Figure 3). We would speculate this could be expected of other Utah juniper and also Rocky Mountain juniper that occur sufficiently north of areas strongly affected by the North American Monsoon.

When detrending the Utah juniper series, we noticed that although the negative exponential curve characterized biologic growth trends in some cases, oftentimes a mean line was more appropriate. We suspect this was partially caused by the absence of a juvenile growth period on many samples, increment cores and older cross-sections, which was common as a result of deterioration and heart rot. Mean growth trends may also be the result of the relatively unpredictable morphology of the stems and branches of this species as it ages (Figure 9). Generally, the older an individual, the less live tissue it supported, resulting in elongated, linear lobes of growth rings, not unlike those seen in ancient bristlecone pine (*Pinus longaeva* D.K. Bailey).

Utah juniper normally exhibits extreme lobate growth, which makes it important to carefully choose where increment cores are to be extracted. However, it is evident (Figure 9c) that in some cases one might remove an increment core from a portion of the stem that is nearly impossible to date. Although we attempted to avoid deep bark fissures between lobes when sampling, we occasionally removed cores that contained mostly bark. Heart rot was also a common problem. Furthermore, circuit uniformity, commonly considered to be required in dendrochronology (Cook and Kairiukstis 1990), is the exception in Utah juniper, not the rule, but this should be expected of plants living in harsh environmental extremes for long periods of time (*e.g.* old individuals of bristlecone pine). Ultimately, a little more time and care is needed when sampling Utah juniper with an increment borer compared to other species with better circuit uniformity.

Utah juniper and Rocky Mountain juniper co-occur in many places, typically with Utah juniper located at the lower elevations, and Rocky Mountain higher (Figure 2). Where they do co-occur, discerning between them in the field can be difficult. One important attribute for identification is that Utah juniper is typically monoecious (Zlatnik 1999), whereas Rocky Mountain juniper and one-seed juniper are typically dioecious (Johnson 2002; Scher 2002). This is not always particularly helpful in the field where cones may be absent or out of reach. Another approach to identification is to break off a relatively large dead branch to view the heartwood coloring. Strong reddish coloration indicates Rocky Mountain juniper, while brownish or yellowish heartwood indicates Utah juniper (Figure 9c). Finally, hybridization between species is likely although only confirmed in Arizona and Wyoming (Zlatnik 1999; Scher 2002).

Utah juniper also has extremely dense wood for a conifer and, in combination with typical irregular stem growth and very dry, brittle heartwood, is very difficult to sample. Utah juniper wood has a very high specific gravity (0.54), one of the highest for conifers, compared to Rocky Mountain juniper (0.45), singleleaf pinyon (0.37), common pinyon (0.50), or Douglas-fir (0.45). The only associated species with a higher specific gravity is curlleaf mountain mahogany (*Cercocarpus ledifolius* Nutt., 0.81) (Chojnacky 1984; Miles and Smith 2009). This makes increment cores difficult to extract, but not impossible. Regardless of the difficulties in sampling, Utah juniper occurs over a large area of the Interior West, and could be highly valuable for characterizing climate of the lowest elevation woody tree habitats. In conclusion, we think success in dating Utah juniper is based on the site/climate characteristics, the skill of the dendrochronologist, and the willingness to put time into it, which we suggest is worthwhile for very strong chronologies.

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